BIM BASED WORKFLOW FOR 4D CONSTRUCTION PLANNING

Giulia Rubiu[1], Emanuela Quaquero[1], Giuseppe Desogus[1] and Giovanna Stocchino[1]
[1] University of Cagliari, Department of Environmental Civil Engineering and Architecture.

Abstract

The studies conducted on Building Information Modeling methodology and its associated tools spotlight the related great improvement in managing the construction phase. This paper shows how BIM4D simulation can boost the accuracy of the temporal and economic forecast of the constructive intervention. This approach can reduce problems related to the incorrect interpretation of the work program because it is able to directly relate the information model with the work program in a single environment. Moreover, this contribution reports the strong improvement in the construction phase management by the integration of BIM 4D methods and tools and a geospatial 3D mapping platform.

Introduction

The building process appears rather complex (Zhang *et al.* 2015) because it is the result of a high number of activities which involve many conflicting issues. The building production deals with prototype: each process is developed just one time. The building site is an open system in which each time is different the output, means and equipment, weather conditions, workers, suppliers and work context. Actually, such features cause low-quality levels of the buildings and low levels of productivity (*ASSOBIM* 2019) and safety in the construction sector (*ASSOBIM* 2020). To deal with these criticalities construction management technics are used. They support work planning and process optimization. These technics and the related tools allow the simulation of many alternative operational scenarios to optimize the process in relation to the variables. However, one of the principal criticalities depends on the methods of the representation of the work plan which do not allow efficient and complete analysis of all the relevant issues. The traditional planning activity produces documents as charts and 2D layout plans. These outputs are totally independent of each other. This last feature does not allow an integrated vision of time and space variables. The integration activity between the work plan and the 2D layout plans are delegated to the capacity of the worker to virtualize mentally the building site evolution. These features cause a difficulty in controlling the interferences between activities and in managing safety issues. In addition, they allow a limited assessment of design alternatives of the building site scenario, to which is added the total absence of an environment for sharing and storing data and information, very useful for the management of the intervention. In this situation 4D BIM (3D + time) simulation (Argiolas *et al.* 2015) (Van and Quoc 2021), could improve the accuracy of the temporal and economic forecast of the constructive intervention. The use of BIM in the planning process can reduce problems related to the incorrect interpretation of the work program because it is able to directly relate the information model with the work program in a single environment. (Van and Quoc 2021). However, the building sector, particularly the building companies, has not yet invested in new organizational models and new digital technologies (*ASSOBIM* 2019), showing deep reticence towards innovation (Ciribini *et al.* 2019). Medium and small companies of the sector still believe that they cannot afford BIM methodology and tools. They assert that the cost of the BIM platform and the skills required are amortized in the case of projects with a significant budget but remain unsustainable for small businesses. The adoption of BIM is widespread in various countries of the world and is also increasing in Italy (Argiolas *et al.* 2015; Van and Quoc 2021), thanks to the thrust deriving from the “BIM Decree”. Despite BIM methodology could lead to interesting advantages (Eastman *et al.* 2011) it is not yet homogeneously implemented in all the steps of the building process. It presents a large use within the design phase but a lower use within the executive phase. The planning of the construction process is fundamental especially in crucial phases. Planning, in addition to improvements in project visualisation, offers greater quality assurance and timely delivery, improved collaboration and communication between participants(Azhar 2011; Georgiadou 2019).

Literature Review and Gap

BIM 4D methodology offers different uses (Agostinelli *et al.*)and advantages (Bataglin *et al.* 2020) on which many studies and experimentations have been conducted. The use for logistics management has been studied (Pham *et al.* 2020; Whitlock *et al.* 2021), for safety management (Antonino *et al.* 2019; Ciribini 2019; Pham *et al.* 2020), for the optimization of the construction process and site layout (Getuli and Capone 2018), for the management of spaces and resources, for the analysis of the workspaces (Mazars and Francis 2020), for the management and simulation of the flows of work vehicles (Sloot *et al.* 2019), for risk mitigation (Martínez *et al.* 2019) and for the detection of space-time interference among activities. The studies on BIM 4D use in the pre-construction phase (Li *et al.* 2009; Balakina *et al.* 2018) provide valid references on implementation methods and procedures, highlighting results and advantages of this methodology: optimization of time, costs, safety, compliance, communication as well as improving the final quality of the product (Getuli and Capone 2018). Due to its impact on safety and productivity issues on construction sites, several site layout planning models have been developed over the past decades. Construction site layout modeling has a strong and close interaction with construction planning, scheduling, and cost estimation processes. The poor representation of the construction site layout can lead to poor quality results, additional costs and project delays (Sebt *et al.* 2008; Diakite and Zlatanova 2020). Some studies define issues and possible solutions in terms of the construction site layout modeling (Sadeghpour and Andayesh 2015). Construction site layout modeling is important for two main reasons: (1) checking of the space available for processing and (2) referring to the territorial context (Sadeghpour and Andayesh 2015). All the resources on a construction site (building elements, temporary structures, materials, equipment, machinery, and workers) take up space and are therefore potential sources of interference among operational tasks. The accurate definition of these taxonomies improves the visual interpretation of the space requirements of the site and sets the stage for the analysis of the space-time conflict. (Karan and Irizarry 2015). Furthermore, the importance of knowing the territorial context in which the construction site is located is clear. The construction site, in fact, is an open system in which the flows to and from the surrounding territorial context have a deep influence on the organization and planning of the operational tasks and the construction site layout (movements to and from landfills for the management of waste materials, transfers from material suppliers, vehicle and pedestrian access, storage areas, etc.). For the above reasons it is clear how strategic the BIM-GIS integration is. BIM-GIS integration research has only begun in the last decade (Su *et al.* 2012). BIM and GIS are two types of systems that manage data at different scales: the physical scale of the building and the scale of the geographic space (Barazzetti and Banfi 2017). It is therefore easy to understand that the integration of these systems can provide valuable support for the management of the construction phase of the building [(Arroyo Ohori *et al.* 2018). The BIM system manages geometric and semantic information useful during the entire life cycle of the building (Butkovic *et al.* 2019), while the geographic information systems (GIS) are able to manage and analyse data associated with a place on earth (Nechyporchuk and Bašková 2020). The differences between the two systems make BIM-GIS integration difficult. The BIM-GIS integration topic includes different approaches and different applications, without a clear path and with a heterogeneous understanding of the term "integration" (De Gaetani *et al.* 2020). Recently some studies reported some results that encourage the combination of these systems and related technologies with the semantic web (Arroyo Ohori *et al.* 2018). Free online resources, including Google Earth (GE), transformed the way design professionals handle spatial data (Di Giuda *et al.* 2017). To deal with unstructured data some studies focused on extended markup language (XML). Web GIS, LandXML, CityGML and KML formats are based on XML (Li and Lu 2018). This language, also adopted by Google Earth, is particularly useful to visualize the site of a specific project. It also presents a good possibility for its integration with BIM oriented tools but this kind of integration to manage the building construction phase is not currently explored (Li and Lu 2018). The survey methods that use geomatic tools, such as total stations, laser scanners to build the context require significant economic resources for the adoption of the equipment as well as a high level of competence for its correct use. In addition, they require a lot of work for both relief and restitution. Resources such as Google Earth, allow taking advantage of data and information related to the context with a sufficient level of precision, proportionate to the needs of small and medium-sized companies of the construction sector, and with reduced technological barriers. (Li and Lu 2018) However, the process of integrating these resources with BIM platforms still requires some manual adaptation procedures.

Research Contribution

The experimentation phase of the research project was conducted on a case study of historical-architectural interest: the Mandolesi Pavilion of the Faculty of Cagliari. It involved the implementation of a 4D BIM approach to defining in detail the evolution of the construction site in a scenario of energy efficiency of the building chosen as a case study. The workflow put in place is divided into three macro-phases starting from a preliminary process of knowledge and information modeling of the building. The 4D BIM of the intervention was developed starting from an information model of the building, already developed in previous research works. To consider the information of the territorial context in which the building is located, an opensource geospatial 3D mapping platform plugin was adopted. It uses the system adopted by Google Earth for the retrieval of geographic information and for their association with the BIM model of the building through a semi-automatic process. The association of digital terrain models to the BIM model of the building allow to obtain a valid support for the subsequent planning phase of the intervention on site. Finally, 4D BIM was obtained by integrating data and information coming from the planning activity of the construction tasks. It is a process that does not require a high level of GIS skills and allows to obtain territorial information quickly and easily. It also allows to reach a level of detail compliance with the needs of small and medium-sized companies of the construction sector in maintenance interventions on the existing buildings. Although the geographic data from Google Earth have already been adopted for various purposes and in association with other tools, currently there are no use cases in the planning of the construction site.

The paper is organized as follows. Section 2, Materials and Methods, presents and discusses the methodology and tools used. In addition, this section presents the case study and the workflow adopted. Section 3 presents the analysis and discussion of the results. Finally, the conclusions and future development are presented in Section 4.

Materials and Methods

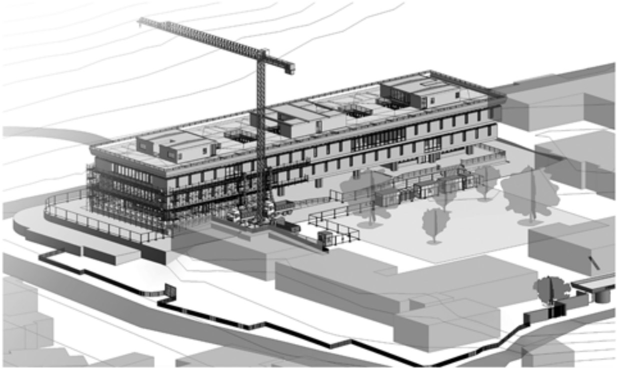

Figure 1: 4D BIM simulation

Case study

The case study, the Mandolesi Pavilion of the Faculty of Cagliari, is a historic building of particular architectural and iconic value designed in 1964 by Enrico Mandolesi and completed in 1970. (Di Giuda *et al.* 2017). It is articulated in an underground floor, a pilotis ground floor and two upper floors. On the pilotis level, there are two floors in elevation with decisive projections; the base uses the level difference with the road to insert a basement that houses laboratories for large equipment and a large double-height Great Hall (Di Giuda *et al.* 2017; Li and Lu 2018). The upper floors are divided longitudinally into three functional areas: those on the edges, which correspond to the projecting parts, include study and research areas; while in the central strip, there are service blocks (toilets, staircase and lift) which define the beginning and the end of a sequence of areas for research and teaching activities, lit by six large cavaedia and two smaller ones. The pilotis system along with the roof, which alludes to the large garden terraces of Le Corbusier, constitute the leisure areas and serve as a mediator space between the two upper floors and the underground floor. Flexibility is the principal element of the programme and is considered by the designer as a “tangible sign of mobility, a fundamental characteristic of our age”. The use of a reinforced concrete frame is therefore understandable since it can create wide projections and providing a flexible internal distribution. In the upper floors, the structural pattern has a regular pitch. It consists of two rows of nine pillars, strongly recessed from the façade, which supports two longitudinal “T”-shaped beams 90 metres long. Cantilever portions are 4 metres on the pilotis level and 5 metres on the roof level. This aspect, along with the slots below the slabs, that denounce the non-structural nature of the façade panels, emphasises the horizontality that governs the geometry of the building. Staircases and lifts are made of exposed reinforced concrete septa, which are independent of the load-bearing structure. The ramps consist of steps prefabricated in-situ that are slotted in the septa and are lit and ventilated by small openings on the wall and by the cavaedia, towards which the distribution corridors overlook. The external wall consists of only 6 cm thick prefabricated concrete panel, with a layer of 3 cm of glass wool, an air gap of 17 cm and a layer on the inside made of solid square bricks 6x6x24, obtained by cutting in half the “double UNI” brick. The concrete panels are fixed on the edge of the slab by "T" elements in profiled iron embedded when the slab is cast. The iron frame is not only the support for the concrete panels but also for the windows that close the slot between the slab and the underlying concrete panels (Sanna *et al.* 2017). The Pavilion is over 50 years old. This time obviously had its consequences in terms of physical obsolescence, thermal comfort, energy consumption and what we now call “building sustainability” and “energy efficiency (Di Giuda *et al.* 2018; Sanna *et al.* 2019). These issues have led to planning a retrofit intervention that focused on the replacement of the entire opaque and transparent building envelope. The workflow, synthetically presented in par. 1.2 (Research contribute), will be detailed in the following section. It is focused on the retrofit intervention to provide support to the planning phase of on-site construction tasks.

Workflow

This paper reports ongoing research which has its roots in PRELuDE3 research goal was to make the energy audit procedures on the existing building stock more efficient, capitalizing the results in an information model. The model allows a faithful representation of the building to plan the most appropriate intervention on a shared basis of knowledge. For this reason, the first steps of the research project focused on the building's recognition analysis to achieve the deep knowledge of it (Sanna *et al.* 2017). Then the selection of the information to be capitalized was carried out and the development of the informative model started (the tool used was Revit Autodesk). Each virtual element (Revit family) that represents the real component of the building was defined in terms of shape, dimension and thickness. Each virtual element was integrated by information and data which referred to function, material features, techniques and constructive technologies used, level and type of degrading, residual performances and indications for maintenance interventions (Di Giuda *et al.* 2018; Sanna *et al.* 2019)]. The BIM model of the building already developed in the Prelude project was a valuable source of information for studying and planning the retrofit intervention. For this reason, it can be considered a starting point for the workflow used in the experimentation. This workflow is divided into two macro-phases as described below.

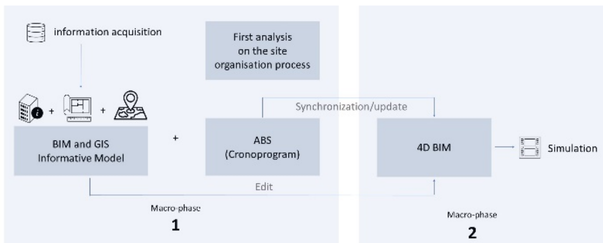

Figure 2: Workflow adopted

Macro-phase 1: 3D model and ABS structure

The workflow started with the creation of the site information model. It was obtained by integrating the BIM information model of the building, the information model of the territorial context and the set of virtual objects that faithfully represent the characteristics and workspaces of the means and preparations necessary to develop the works. The CADtoEarth ™ plug-in (Sadeghpour and Andayesh 2015) for Revit was used to create the context information model.

Figure 3: Geospatial 3D mapping platform CADtoEarth.

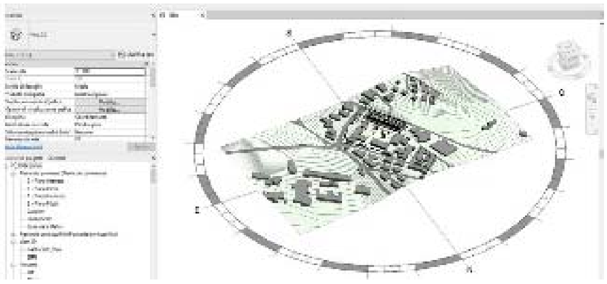

Figure 4: The spatial model extracted from the plug-in and integrated with the building information model and road layout into software Autodesk Revit.

It allows to frame the site area and to represent it as a three-dimensional-information model through internal data processing. It represents the topography of the area together with simple volumes that reproduce the surrounding buildings. The information model of the context obtained was associated with the BIM model of the building. However, it was useful to manually add some details near the building to represent the border elements between the building and the context (ramps, stairways, etc.). In addition, 2D CAD floor plans were used at this stage to verify and correct the terrain model elevations. The integration of a few control points, allow the centimetre accuracy of the reconstruction of the area in a much faster way than a traditional process. Based on the integrated building-context information model, a preliminary analysis was made of the temporary equipment necessary to carry out the tasks on site and suitable for the specific situation. The next step was importing into the information model the virtual objects that faithfully represent the characteristics and workspaces of the vehicles and equipment chosen. With this approach, various construction site layouts have been developed. Among these, the one capable to optimize the work and giving the least discomfort to the ordinary activities of the building was selected.

A first advantage for the planning of construction site activities was obtained by the 3D model of the building and the context in which it is established. The Mandolesi pavilion is located inside a university campus which is characterized by the dense presence of buildings of different height and size. The ground of the Campus has numerous height differences, there are predefined pedestrian and vehicular paths and a big garden with planting and fixed furniture to be preserved. The Mandolesi pavilion has a basement that is larger than the footprint of the upper floors above ground. This basement is roofed with a concrete slab not suitable for the weight of the vehicles and on which are located many skylights. All these aspects made the 3D model very useful. It can create a reliable informative base for developing the most suitable construction site layout. The university campus to which the Mandolesi pavilion belongs is composed of further buildings and is heavily frequented by students, researchers, and administrative staff whose activities must be able to continue without interruptions but also without risks related to interference with the work site activities. Starting from these critical points, two different construction site layouts were configured to avoid the complete closure of the building and of a very large portion of the external spaces shared with the other buildings. The analysis of the information about the building, its internal distribution, the activities carried on within it (rooms uses) as well as the characteristics of the building's context led to the development of two site layouts in temporal sequence. This solution could guarantee only the partial closure of the building under intervention and the adjacent external spaces. Using a three-dimensional prototypical approach, the vehicles and equipment to be used on the construction site were integrated into the 3D model. The fence path was carefully chosen, integrating the needs of the campus users with the needs of the staff employed on the site. The virtual fence object was inserted, validating, in relation to the specific context, the type, the height and the dimensions of each module. Moreover, vehicles and pedestrian accesses were specified by inserting virtual objects in the model showing type, position, and size of those to be used during the works. The 3D model was then integrated with virtual objects representing the vehicles to be used, the prefabricated boxes and toilets for workers, and the tower crane. The 3D model validated the crane's dimensional characteristics (tower height of 35m and boom length of 40m) and its specific dimensions (3.5x3.5m wide base) in relation to the needs of replacing the vertical opaque and transparent envelope; the space provided for the stacking of waste materials and storage areas for the envelope components to be installed was also included in the model. The introduction of the virtual scaffolding object chosen for the specific project made it possible to achieve a realistic configuration, considering in a detailed and specific manner the coherence with the morphological characteristics of the building (e.g., the overhangs of one floor with respect to the upper one) and of the ground and the relative height differences. Finally, the inclusion of virtual objects representing the rubble disposal pipes for dropping demolition materials from the innermost layers of the opaque envelope to the ground was fundamental in defining their position and necessary length in relation to the paths allowed for lorries to collect and transport this material to the landfill. With the assessments and the preliminary choices made, it was possible to proceed with the decomposition of the construction process using the ABS (Activity Breakdown Structure) technique. The processing tasks and sub-tasks were then identified, and the work program was defined. Within the Microsoft Project software, it was possible to schedule the operations: the dependency constraints between the tasks were imposed; resources (workers, materials, equipment and means) have been assigned to each activity and then their times were estimated. The specific safety measures were also evaluated by defining the use of precise DPCs to be adopted during processing.

Macro-phase 2: 4D BIM

In the second macro-phase, the 4D BIM model of the intervention was developed. The elements of the BIM information model intended to converge towards the 4D BIM environment have been identified through a parameter. This parameter, identified through a unique code (Argiolas *et al.* 2015), creates a connection between the activities of the work program developed within the tool Project Planner and all the components of the construction site information model, including all the necessary means and equipment. After these additions, exports were made: the information model of the construction site was exported in NWC format, while the work program was exported to MPP. These were then imported into Navisworks taking care to use the suitable configurations to keep all the useful data. To ensure that the files can also be updated and synchronized, they were saved in NWF format.

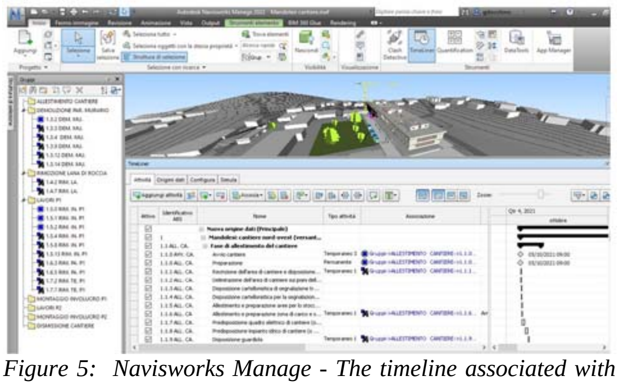

Figure 5: Navisworks Manage - The timeline associated with ABS.

In this phase, to obtain a good program and a realistic simulation of the evolution of the construction site, the times of the activities were estimated. The estimated times were integrated into the Microsoft Project operating program and then, through synchronization, reported in the 4D BIM environment.

The movement of the means and equipment were then simulated thanks to the tools available in the Navisworks application. Completed this process it was possible to export the simulation in the form of video.

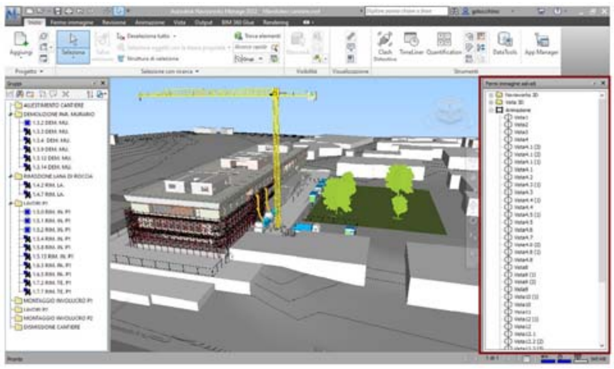

Figure 6: Navisworks Manage - Creating a 4D Simulation.

The 4D BIM model was used to simulate the operational sequences and to validate and/or modify the choices made in the previous phase. The simulation was essential to verify the feasibility of the two consecutive construction site layouts and the partial closure of the building and adjacent outdoor spaces. Ensuring the total absence of interference between the activities of the building in the normal operational phase and the site activities to be carried on in the portion of the building involved in the first phase of the intervention was central. The position of the tower crane in both layouts was validated. In more detail, the removal of the original envelope panels and fixtures and the subsequent replacement with new panels and fixtures is a critical operation due to the considerable size and weight of each element. The 4D simulation of this operation involving scaffolders and cranes made it possible to study in detail the various operating sequences, the associated safety risks and, consequently, the most suitable procedure and protective devices to guarantee the safety of the site operators involved in this work, but also of the users outside the site who pass through areas extremely close to the work areas. This simulation is extremely effective in training the operators involved, who can have a clear and realistic dynamic representation of how they will have to carry on that activity, with what procedures and equipment. In addition, the 4D simulation was essential to verify the congruence between the vehicles chosen and inserted in the 3D model, their workspaces, and paths for their movement on site and the workers' pedestrian flows. Because the spaces inside the site are very limited, the dynamic representation of the vehicles and operators made it possible to identify several interferences and to resolve them by redefining these paths (in particular, the pedestrian path adjacent to toilet for the workers was redefined to solve the initial overlap with the route of the vehicles). The 4D simulation has allowed to verify the operating sequences identifying in some cases space-time interferences. For example, for scaffold set up and replacement of the transparent and opaque envelope activities, the 4D simulation showed that it was impossible to easily perform the removal of the panels and frames on the first level with the presence of the scaffold to the top level of the building. During this work, the scaffold, with its bracing and safety railing, as well as the frames themselves, represents an obstacle to the passage of the panels and frames of considerable size to be removed at the first level; for this reason, the phases and their succession have been reorganized. Originally, it was planned to set up the entire scaffolding, carrying on with the removal of the envelop elements from the top level of the building to the lower ones. These activities sequence immediately shows an important interference between the movement of the envelope elements to be removed at the first level of the building and the scaffolding frame. Hence a new activities sequence is planned. It forecasts to set up the first level of the scaffolding, to remove panels and fixtures of the building envelope related to this level, to set up the scaffolding frame on the second (the last) level of the building and finally to remove its envelope elements. Therefore, the scaffolding set up was divided into two different phases. Besides the reconfiguration of the scaffolding set up activity, the new envelop elements installation sequences are rearticulated. Because the entire scaffolding frame causes interference also during the new envelope elements of the first level of the building set up, the new activities sequence forecasts to remove the scaffolding frame of each level of the building before setting up the new envelop of the same level of the building.

Conclusion and future research

The production process in construction, which has always been kept far from innovation experiences compared to other economic sectors, today must deal with an inevitable growth process in which the keywords are undoubted: planning, digitization, sharing. The planning and programming activities can make the whole production process more balanced with a high probability of achieving the set objectives. The purpose of the Construction Management approach is to foresee the development of the intervention to optimize construction times, the use of human resources and available materials and the costs as well as to meet the quality and customer performance requirements. There are many planning and programming tools that can offer valid support for the management of the execution phase. However, many critical issues are associated with these tools, including the representative methods that do not allow efficient and complete analysis of all the critical issues. The traditional planning activity produces documents as charts and 2D layout plans. These outputs are totally independent to each other. This last feature does not allow an integrated vision of time and space variables. The integration activity between the work plan and the 2D layout plans is delegated to the capacity of the worker to mentally virtualize the building site evolution. These features cause difficulty in controlling the interferences between activities and in managing safety issues. In addition, they allow a limited assessment (in terms of number and quality) of design alternatives of the building site scenario, to which is added the total absence of an environment for sharing and storing data and information, very useful for the management of the intervention. This research shows how 4D BIM simulation could improve the accuracy of the temporal and economic forecast of the constructive intervention. The use of BIM in the planning process can reduce problems related to the incorrect interpretation of the work program because it is able to directly relate the information model with the work program in a single environment. The development of the animation of the operational program capable of showing the building under construction in 3D from start to finish, guarantees:

-greater effectiveness in communicating the steps of the works to the clients; -a better understanding of the scope and timing of the work of subcontractors and suppliers involved. The simulation of the construction phases also allows the possibility of making conscious and effective choices with respect to the site layout most suitable for the specific case, the operational sequences, the resources to be allocated, the actual execution times, safety management, etc. All this is achievable if the informative modeling of the building is accompanied by the modeling of the territorial context. The benefits of BIM-GIS integration are currently stimulating research. However, the survey methods that use geomatic tools, such as total stations, laser scanners to build the context require significant economic resources for the adoption of the equipment as well as a high level of competence for its correct use. In addition, they require a lot of work for both relief and restitution. These systems are prohibitive for small and medium-sized companies engaged in the maintenance and refurbishment of existing buildings. In this regard, the contribution proposes the use of resources such as Google Earth which allow taking advantage of data and information related to the context with a sufficient level of precision, proportionate to the needs of small and medium-sized companies of the construction sector and with reduced technological barriers. It is a process that does not require a high level of GIS skills and allows to obtain territorial information quickly and easily. The results obtained during the experimentation on the building chosen as a case study confirmed the advantages. However, this approach leads to a necessary growth of all the subjects involved in the construction phase of a building. A great competence in dealing with BIM platforms and their interaction with construction management tool is essential. However, this methodological approach it's useful when we deal with interventions on the existing buildings of high architectural and iconic value as the case study reported on this contribute. In these cases, many issues are intertwined: limited spaces in which construction site layout is articulated; buildings in which relevant activities are carried on (they cannot be totally closed, and the development of more temporal subsequent layouts is necessary to reduce impact on the ordinary activities of the buildings and of the adjacent spaces). In this kind of construction sites safety management is a critical issue both for workers and inhabitants who fill adjacent buildings and external spaces.

This contribution does not intend to propose an overturning of good practices relating to traditional planning and programming activities currently in use but rather an integration and optimization with BIM and GIS tools. However, it is important to highlight the need to improve the geospatial 3D mapping platform systems in terms of quality and accuracy of the data relating to the territorial context. This would ensure the reduction of the manual adjustment activity that is currently necessary to obtain a good integration between the building model and the model of the territorial context. Finally, the results presented will be further developed through the integration of technologies capable of improving the approach to operational planning. In this regard we will refer to Virtual Reality, Augmented and Mixed Reality, Game Engine (Getuli and Capone 2018; Zaker and Coloma 2018; Ciribini 2019; Ciribini *et al.* 2019) which are showing strong potential (Delgado *et al.* 2020).

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